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Dr. Arje Nachman
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Subject: Final Report for AFOSR Grant FA9550-09-1-0386, "Aerosol Impacts on Cirrus Clouds and High-Power Laser Transmission: A Combined Satellite Observation and Modeling approach"
Covering period: 06/15/09-11/31/09

Dear Dr. Nachman:

During the grant period, we have focused on the use of the Weather Research Forecast (WRF) model for cirrus cloud simulation and prediction in conjunction with satellite observations to support the overall ABL operation. Below are our specific accomplishments.

1. Implementation of Improved Radiation and Ice Microphysics Parameterizations and Increased Vertical Layer in WRF

We have implemented in WRF a new radiation module, referred to as Fu-Liou-Gu radiation parameterization [Gu et al. 2010], which is a modified and improved version based on the Fu-Liou radiative transfer model [Fu and Liou 1992, 1993]. A combination of the delta-four-stream approximation for solar flux calculations and delta-two-and-four-stream approximation for IR flux calculations has been implemented in this scheme. This combination has been proven to be computationally efficient and at the same time to produce a high degree of accuracy. The incorporation of nongray gaseous absorption in multiple scattering atmospheres is based on the correlated *k*-distribution method. The solar and IR spectra are divided into 6 and 12 bands, respectively, according to the location of absorption bands. In the solar spectrum, absorption due to H_2O (2500-14500 cm^{-1}), O_3 (50000-14500 cm^{-1}), CO_2 (2850-5200 cm^{-1}), and O_2 (A, B, and γ bands) is taken into account. In the thermal IR region, absorption due to H_2O (0-2200 cm^{-1}), CO_2 (540-800 cm^{-1}), O_3 (980-1100 cm^{-1}), CH_4 (1100-1400 cm^{-1}), N_2O (1100-1400 cm^{-1}), and CFCs (in the 10 μm region) is included. The continuum absorption of H_2O is accounted for in the spectral region 280-1250 cm^{-1}. In addition to the principal absorbing gases listed above, we included absorption by the water vapor continuum and a number of minor absorbers in the solar spectrum, including CH_4, N_2O, NO_2, O_3, CO, SO_2, O_2-O_2, and N_2-O_2. This led to an additional absorption of solar flux in a clear atmosphere on the order of 1-3 W/m^2 depending on the solar zenith angle and the amount of water vapor employed in the calculations. Parameterization of the single-scattering properties of ice crystals of various shapes and sizes followed the recent work presented in Liou et al. [2008].

We have also incorporated an ice microphysics parameterization to include interactive mean effective ice crystal size (D_e) in connection with radiation parameterizations [Liou et al. 2008].

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14. ABSTRACT
The objective of this basic research effort is to provide the theoretical foundations for modeling/simulating the interaction of aerosols and ice at high altitudes (near and above the tropopause). The AF, together with the ABL SPO (through the MDA), anticipate that aerosols/ice will impact the efficacy of the ABL and the ability to predict possible impacts is of great value. The PI and his colleagues will interrogate a number of conceptual schemes which incorporate cloud microphysics (with 6 classes of moisture species together with actual ice concentrations). Particular attention will be paid to ice nucleation scenarios.

15. SUBJECT TERMS

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Correlation analysis between ice water content (IWC) and D_e has been carried out using a large set of observed ice crystal size distributions obtained from a number of cirrus field campaigns in the tropics, midlatitude, and Arctic. We showed that IWC and D_e are well-correlated using this regional division. For the current study, parameterization of D_e for midlatitude was employed, in which IWC ranges from ~10^{-4} – 10^{-1} g/m^3, while D_e has values from ~30-140 μm. Ice crystal shape consists of 60% bullet rosettes and aggregates, 20% hollow columns, and 20% plates for ice crystal maximum dimension (L) > 70 μum, while for L < 70 μm, the shape factor consists of 50% bullet rosettes, 25% plates, and 25% hollow columns. Having included all the preceding ice crystal size and shape features, the Fu-Liou-Gu scheme is now an ideal tool for the simulation of radiative transfer associated with cirrus clouds in weather and climate models.

Finally, in connection with the preceding radiation and cloud microphysics parameterizations, we have increased the original WRF vertical layer from 28 to 65, particularly with an improved resolution above 500 mb where cirrus clouds normally occur.

2. Real Case Cirrus Cloud Simulation and Validation

Cirrus cloud cover has been increasing over the Northeastern Pacific Ocean since 1970's, particularly during spring, due, in part, to increases in upper atmospheric humidity as well as the presence of contrails and the contrail cirrus formation and spreading as a result of trans-Pacific air traffic [Minnis et al. 2004]. Over this same region, non-frontal thin cirrus clouds were observed and reported by military pilots during test flights. For these reasons, we acquired relevant MODIS/Terra/Aqua daytime and nighttime images for March 29 and 30, 2007, over the northeastern Pacific Ocean and western United States. The following is a list of MODIS images: Terra Daytime on March 29, 2007, at 1825 UTC; Aqua Daytime on March 29, 2007, at 2140 UTC, and March 30, 2007, at 2045 UTC; Terra Nighttime on March 30, 2007, at 0530 UTC, as shown in Fig. 1(a) – (d). For comparison purposes, we also acquired GOES-11 visible and IR images over the same general area from the NOAA website for the dates and times that were close to MODIS/Terra/Aqua overpasses: March 29, 2007, at 1830 UTC; March 29, 2007, at 2130 UTC, and March 30, 2007, at 2030 UTC; Terra nighttime on March 30, 2007, at 0530 UTC, as shown in Figs. 1(e)-(h). Both MODIS and GOES-11 observations showed the presence of frontal and non-frontal ice clouds at the dates and times listed above over coastal and western United States areas.

Based on the observed cases, the model domain has been selected to center at 35 N, 120 W and cover the area from 135 -105° W and 20 – 45° N. We have used a horizontal resolution of 30x30 km2, while the bottom-top, south-north, and west-east dimensions are 28x97x112. Initial and boundary condition data employed are the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis on a 1.0x1.0 degree grid, continuously at every six hours. This product is available from the Global Forecast System (GFS) that is operational four times a day in near-real time at NCEP. We have performed 48-hour model integrations in conjunction with the observed cases.

To examine the ability of WRF for the simulation of cirrus clouds and to investigate the effects of radiation processes and the vertical model resolution in the simulation, the following three experiments have been designed. The CTRL experiment is the control run, which includes the radiation scheme, Lin's ice microphysics scheme, and a vertical resolution with 28 model levels originally used in WRF. The RADI experiment is identical to CTRL except that the Fu-Liou-Gu radiation scheme was employed. In the VERT experiment the number of model level in

the RADI setup was increased from 28 to 65, with the improved resolution above 500 mb where cirrus clouds normally form.

We first evaluated the model performance by examining the simulation results determined from the three experiments. Figures 2a-2d show the simulated ice water path (IWP) from CTRL at 1800 UTC (Fig. 2a) and 2200 UTC (Fig. 2b) on March 29; and 0600 UTC (Fig. 2c) and 2100 UTC (Fig. 2d) on March 30, 2007. Figures 2e-2h and Figs. 2i-2l illustrate the simulation results from RADI and VERT, respectively. These results are compared with the corresponding MODIS (Figs. 1a-1d) and GOES-11 (Figs. 1e-1h) images, which display cirrus cloud cover close to the preceding times. The frame in the GOES-11 images represents the model domain. The three model simulations appear to capture essentially all the observed cirrus cloud patterns, including those associated with the frontal system off the west coast and some non-frontal ice clouds to the west of southern California and Mexico. Cirrus clouds over the western United States, including Wyoming, Utah, Colorado, Arizona, and New Mexico, as shown in both MODIS and GOES-11 images, have also been well simulated in the model. The frontal cirrus clouds off the west coast were observed to travel from west to east and began to move over land starting at 0600 UTC, March 30, 2007 (Fig. 1g). This migration has been well simulated and reproduced (Figs. 2c, 2g, and 2k). The cloud dissipation process when cirrus clouds moved over land is demonstrated in both observations and model simulations (Fig. 1g and Figs. 2c, 2g, and 2k). Compared with the simulation results from CTRL, the new radiation module that has been implemented in WRF produces the cloud field displayed in satellite observations. The experiment VERT generates a better agreement with satellite observations in terms of cirrus cloud cover. The CTRL produces lower coverage as well as smaller IWP for frontal and non-frontal cirrus clouds compared with those simulated from VERT. With the improved radiation scheme and increased vertical resolution, we have illustrated that WRF is capable of generating more reasonable cirrus cloud water distributions and life cycle, especially those associated with the frontal system.

3. Discussions and Conclusion

The effects of radiation and the vertical resolution on cirrus simulations can be examined by comparisons among the three experiments. Simulated differences in IWP between RADI and CTRL at 1800 UTC on March 29 (Fig. 3a) demonstrate the effect of different radiation schemes used in the model, while those between VERT and RADI (Fig. 3b) reveal the impact of increased vertical resolution on cloud cover. With the improved radiation scheme, more cirrus clouds are simulated near the cyclone center off the west coast as well as over central Oregon (Fig. 3a), indicating a better agreement with the observations (Fig. 1e). With the implementation of this new physically-based radiation module, WRF is now better suited for the study of cirrus cloud simulations as well as for the investigation of aerosol-cloud-radiation interactions. Vertical resolution plays a significant role in the simulation of cirrus clouds. With an increased vertical level, the model has been shown to produce more clouds over Wyoming, Utah, and Colorado. Simulated IWPs associated with the frontal system have also been enhanced with a higher vertical resolution (Fig. 3b).

The numerical simulation of high cirrus clouds is a complex and difficult scientific task in regional weather and climate modeling studies. We have demonstrated that WRF can reproduce reasonably well the observed cirrus cloud fields and their movement and dissipation processes, especially those associated with the large-scale frontal system. Additionally, we have illustrated that the enhanced vertical resolution significantly improves simulated cirrus cloud distributions due to its impact on vertical velocity field and the associated regional circulation. With the newly

implemented radiation scheme, the simulation of IWPs has been improved for frontal and non-frontal cirrus clouds. In summary, the new radiation module has been demonstrated to work well in the WRF model and can be used for future studies related to cirrus cloud formation and evolution and aerosol-cloud-radiation interactions.

Publication

Ou, S. C., K. N. Liou, X. Wang, R. Hansell, R. Lefevre, and S. Cocks, 2009: Satellite remote sensing of dust aerosol indirect effects on ice cloud formation. *Appl. Opt.*, 48, 633-642.

Gu, Y., K. N. Liou, S. C. Ou, and R. Fovell, 2010: Cirrus cloud simulations using WRF with improved radiation parameterization and increased vertical resolution. *J. Geophys. Res.*, to be submitted.

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During the reporting period, the AFOSR grant partly supported S. C. Ou, Senior Research Scientist, and Y. Gu, Associate Researcher.

Respectfully submitted,

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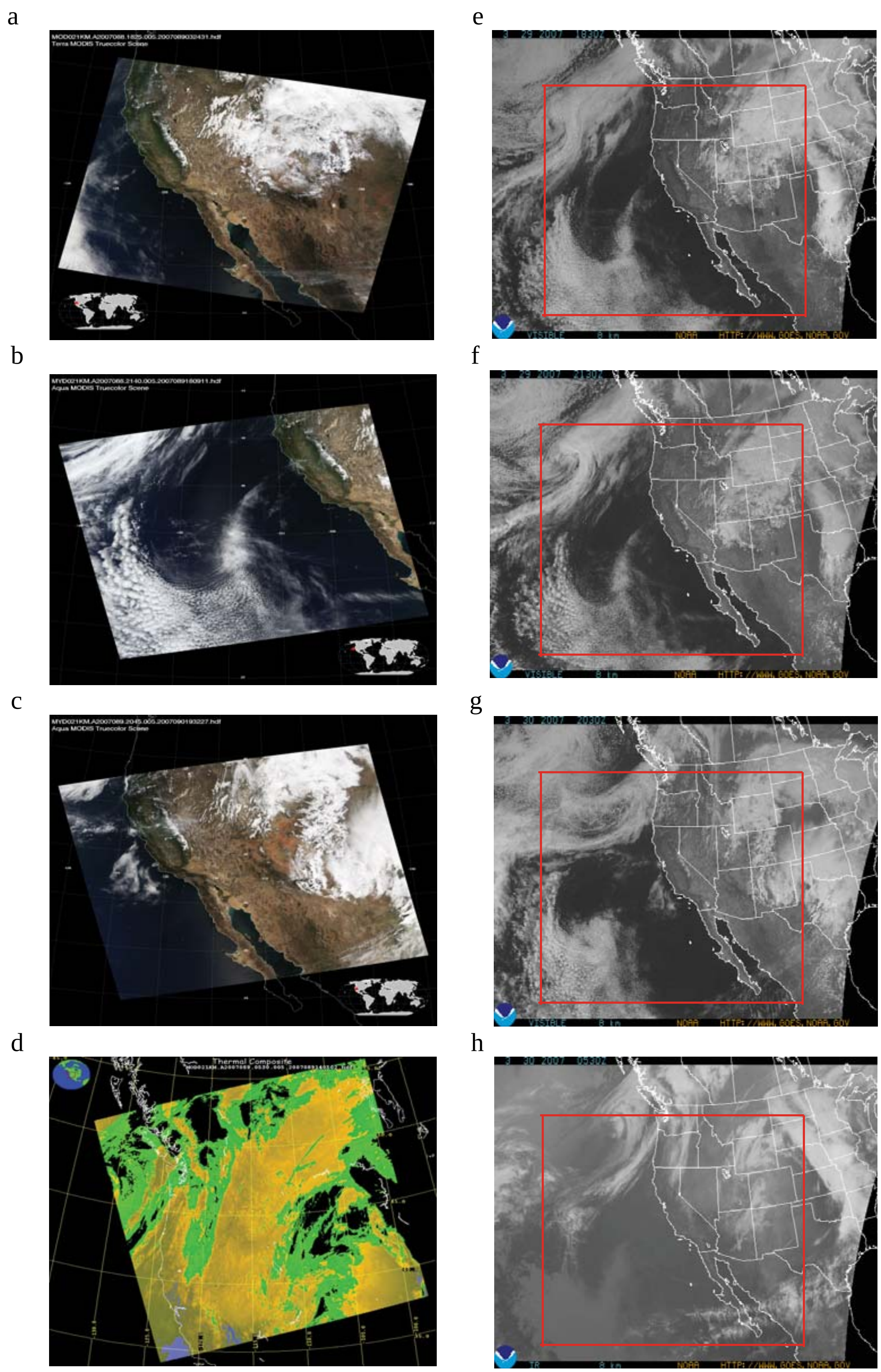

Fig. 1 Observed MODIS (a-d) and GOES-IR (e-h) images at 1800 and 2200 UTC on March 29; and 0600 and 2100 UTC on March 30, 2007.

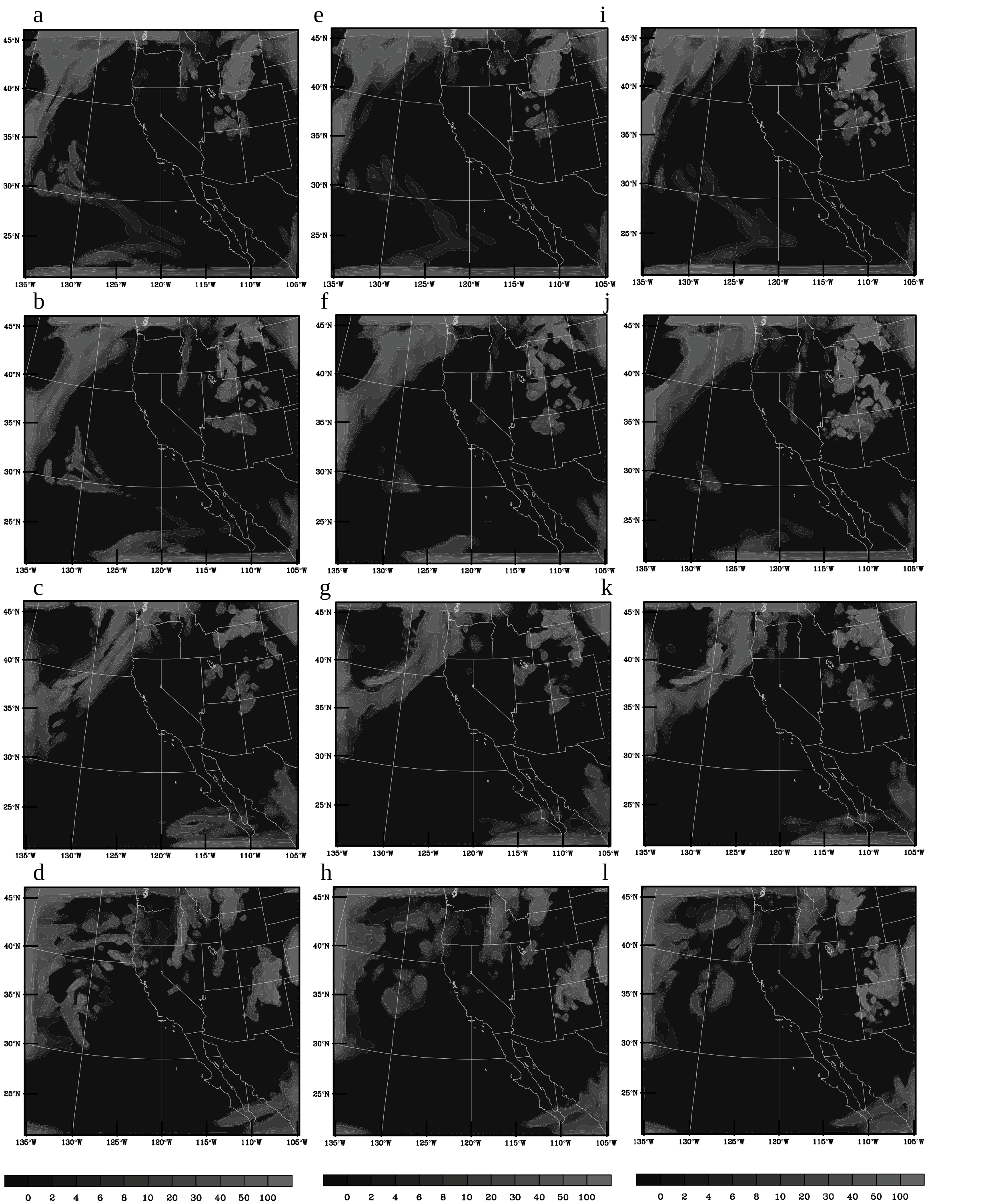

Fig. 2 Model simulated IWPs from the experiment CTRL (a-d), RADI (e-h) and VERT (i-l) at 1800 and 2200 UTC on March 29; and 0600 and 2100 UTC on March 30, 2007.

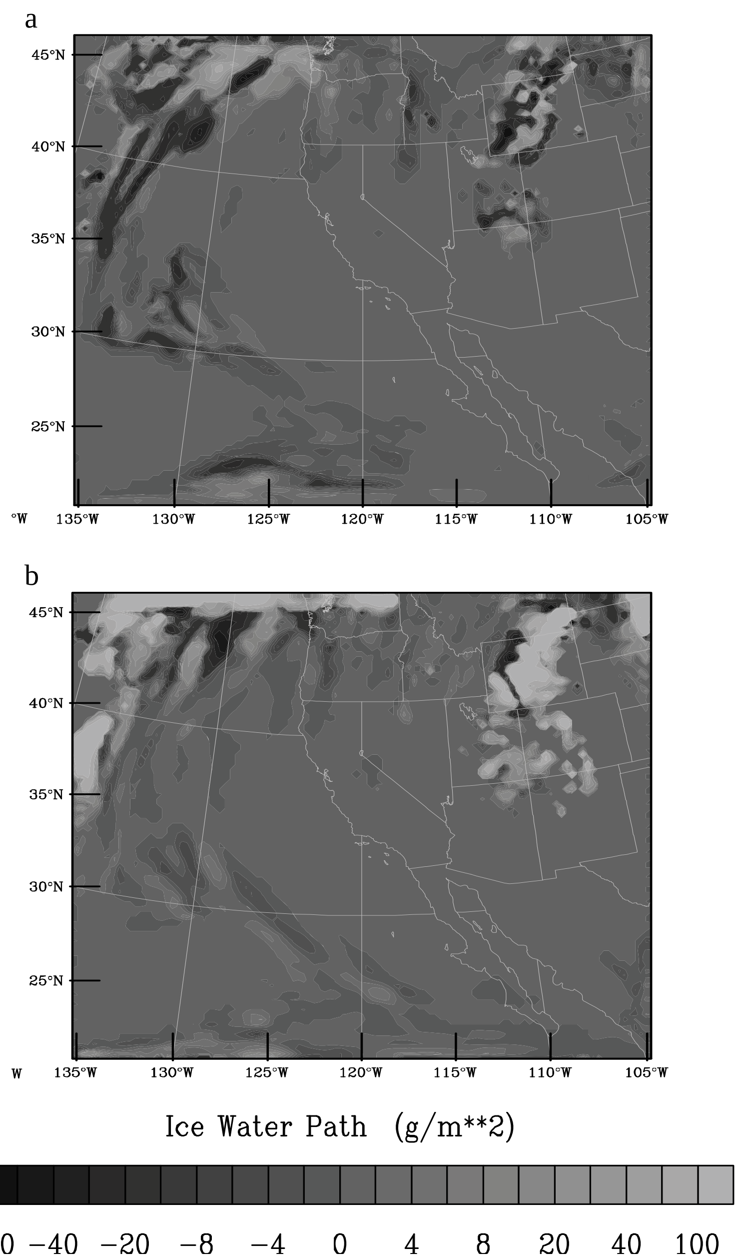

Fig. 3 Simulated differences in IWP between (a) RADI and CTRL and (b) VERT and RADI at 1800 UTC, March 29, 2007.